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Comparative analyses of different biogenic CO_2 emission accounting systems in life cycle assessment

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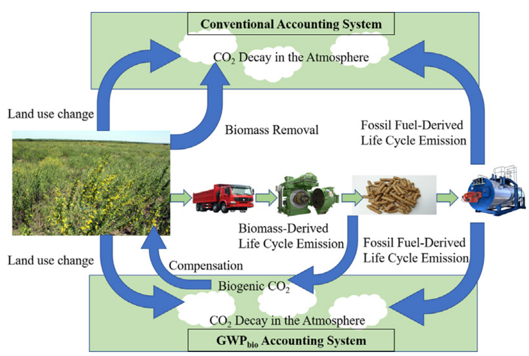
HIGHLIGHTS

- Integrate biomass accumulation model and LCA to account biogenic CO_2 emission
- Compare the difference between new and conventional methods
- Illustrate the models using a case study of caragana-to-pellet system
- Obtain low emission in new method which encourages the use of biomass

GRAPHICAL ABSTRACT



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ABSTRACT

The biomass-derived CO_2 emission is usually treated as neutral to climate change. However, due to the stay of biomass-derived CO_2 in the atmosphere, many researchers believe that biomass-derived CO_2 also has climate change benefit. Therefore, many methods to account the global warming potential of biomass-derived CO_2 (GWP_{bio}) were proposed. Based on those new methods, we developed an accounting system for climate change impact of biomass utilization in this study, and compared it with the conventional accounting system which follows the carbon neutral assumption. A case study of caragana-to-pellet bioenergy production system was simulated to test the performance of the GWP_{bio} accounting system. The CENTURY model was used to simulate carbon dynamics of caragana plantation in the Loess Plateau in China, and life cycle assessment (LCA) model was developed to estimate the life cycle emissions of the caragana-to-pellet system. Attributed to short rotation of caragana plantation and fast biomass accumulation after harvest, the GWP_{bio} values around 0.044 were obtained. When the GWP_{bio} was applied to LCA, significant high life cycle CO_2 emission was found in comparison to the conventional method. However, the GWP_{bio} accounting system has lower positive climate change impact than the conventional accounting system in assessing the overall impact of biomass utilization. This indicated that the application of GWP_{bio} accounting system would encourage the utilization of biomass and allow a fair comparison with fossil fuels. In the sensitivity analysis, we found the accounting system was sensitive to biomass accumulation and all the corresponding factor affecting biomass accumulation.

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1. Introduction

In biomass utilization, biomass-derived carbon emissions will be absorbed by plant regrowth through photosynthetic production effect. Therefore, the biomass-derived carbon emission is presumed neutral to global warming when analyzing the climate change impact of biomass utilization (UN FAO, 2008; Zeman and Keith, 2008), and biomass is considered as an attractive substitution to fossil energy to mitigate global climate change (Lamers et al., 2015). Based on the carbon neutral assumption, current guidelines for estimating greenhouse gas (GHG) emissions exclude biomass-derived carbon emissions, such as the guidelines by the Organization for Economic Cooperation and Development (1991), the European Commission (2009), and the American Clean Energy and Security Act (Waxman and Markey, 2009). In the guideline compiled by the Intergovernmental Panel on Climate Change (IPCC), biogenic carbon emissions are also ignored in estimating climate change impact because they are already fully accounted in the Agriculture, Forestry and Other Land-Use sector (IPCC, 2006). The carbon neutral assumption practically reduced the complexity of carbon footprint analysis in bioenergy systems. However, the assumption may be inaccurate due to the disregard of carbon uptake dynamics, carbon decay in the atmosphere and land use change impact (Liu et al., 2018). Moreover, the assumption causes an unfair comparison of climate change impact between bioenergy and fossil fuels.

To analyze the climate change impact of biomass utilization, life cycle assessment (LCA) is a widely used tool. It was first proposed in 1970 (Hunt and Franklin, 1996) and fully developed in the early 1990s (Boustead, 1996). The LCA studies have been conducted on many different bioenergy products. Based on the zero global warming potential assumption of bioenergy, the mainstream LCA studies neglect the climate change impact of biomass-derived carbon emissions in the study of bioenergy systems. In a review of LCA studies in the Pan American region, Shonnard et al. (2015) found that most of the 74 LCA studies presumed carbon neutrality. Røyne et al. (2016) reviewed 101 LCA studies of forest products and identified the common practices in assessing climate change impact. They found that 87% of the cradle-to-grave LCA models excluded biogenic carbon emissions in climate change impact assessment. The default methods in current popular environmental analysis tools, such as SimaPro and GaBi, usually treat biomass-derived carbon emissions as carbon neutral (Frischknecht et al., 2007; Pachauri and Reisinger, 2007).

Because of the above reasons, the estimation of global warming potential of biomass-derived CO_2 (GWP_{bio}) is critical to apply in the LCA model. The application of GWP_{bio} is straightforward by multiplying the amount of biomass-derived CO_2 emission and GWP_{bio}. Because biomass-derived CO_2 is emitted by a one-time combustion of biomass and stays in the atmosphere for many years (Cherubini et al., 2011), the GWP_{bio} should be a non-zero coefficient. To calculate GWP_{bio}, many studies have been conducted to develop a metric method (Cherubini et al., 2011; Bright et al., 2012; Guest et al., 2013; Liu et al., 2017b). The metric method is based on the relative radiative forcing during the persistence of biomass-derived CO_2 in the atmosphere. The radiative forcing is the difference of solar radiation absorbed by a greenhouse gas and reflected back to space. Based on this concept, the GWP_{bio} values ranged from 0.34 to 0.62 in slow-growing forests (Cherubini et al., 2011). A global scale study of forest bioenergy indicated that the GWP_{bio} values varied between 0.3 and 0.7 (Cherubini et al., 2016). Liu et al. (2017b) calculated the GWP_{bio} in slow-growing forests by considering the decomposition of unharvested biomass and found a lower GWP_{bio} (0.21–0.32). When the short rotation coppice (e.g., willow, poplar, caragana) was used for energy, the GWP_{bio} was close to 0.04.

The earlier studies on GWP_{bio} could effectively improve the accuracy of LCA in accounting for carbon emission and assess climate change impact. However, more detailed studies are required to conduct on the consequence of this accounting method in assessing climate change impact of biomass utilization. The analyzed consequence will provide more persuasive evidences for the consideration of biomass-derived CO_2 emission. In this study, the main objectives are: (1) integrating the biomass accumulation model and LCA model to comparatively analyze the difference of conventional method (carbon neutral) and GWP_{bio} method (carbon unneutral) in assessing climate change impact of bioenergy system; (2) exploring the factors that affecting the difference between the two accounting systems by a case study conducted on a caragana-to-pellet system.

2. Materials and methods

2.1. Accounting systems

This section introduces the integration process of the carbon dynamics model (CENTURY model) and the LCA model in the CENTURY and LCA models section. The integration is the basis of the GWP_{bio} accounting system. The comparison between the conventional method and the GWP_{bio} method is described in the Conventional method vs. GWP_{bio} method section.

2.1.1. CENTURY and LCA models

In this study, the carbon dynamics of biomass regrowth was simulated by the CENTURY4.0 model with weather data and site information as inputs (Fig. 1). The CENTURY model was developed by Natural Resource Ecology Laboratory of Colorado State University and is widely applied to simulated many different vegetation types (Parton et al., 1987). The model is a soil carbon dynamics model and firstly used for cropland/grassland simulation simulate. Recently, the model was also applied to the simulation of energy crops (e.g., switchgrass, Lee et al., 2012). Before the model is used for a specific energy crop, intensive calibration and validation were required to increase the accuracy of the simulation (the detailed process can be found in the Case study section). To obtain an equilibrium state of soil organic carbon, the CENTURY model was initiated by a 2000-year spin-up based on the historical land use and climate data in this simulation.

The outputs of the CENTURY model include removed biomass, biomass accumulation after harvest and soil carbon storage. Removed biomass and biomass accumulation after harvest are required information to determine the GWP_{bio} value (detail can be found in the Supplemental information). Both GWP_{bio} and removed biomass are critical inputs in the LCA model (Fig. 1). The application of GWP_{bio} is straightforward that the climate change impact of biomass-derived CO_2 emission is the product of GWP_{bio} and the CO_2 emission from biomass combustion. The soil carbon storage is necessary to calculate the CO_2 emission due to land use change. The CO_2 emission from land use change is frequently accounted in the estimation of climate change impact of biomass utilization (Liu et al., 2017b).

2.1.2. Conventional method vs. GWP_{bio} method

In conventional LCA, biomass-derived CO_2 emission is treated as no positive global warming potential. However, this fraction of CO_2 emission should be fully accounted in the Agriculture, Forestry and Other Land-Use sector (IPCC, 2006). Therefore, the CO_2 emission due to biomass utilization ($EMISSION_{T1}$) is calculated as follows:

$$EMISSION_{T1} = EMISSION_{luc} + EMISSION_{tra} + EMISSION_{fossil} \quad (1)$$

where $EMISSION_{luc}$ is the emission due to land use change, $EMISSION_{tra}$ is CO_2 converted from removed biomass, $EMISSION_{fossil}$ is the CO_2 emission in the LCA model when treat biomass-derived CO_2 as neutral. In this study, we accounted all carbon in biomass as CO_2 emission.

In the GWP_{bio} method, biomass-derived CO_2 also has unneglectable climate change impact during its stay in the atmosphere. The portion of biomass regrowth to compensate biomass-derived CO_2 emission should

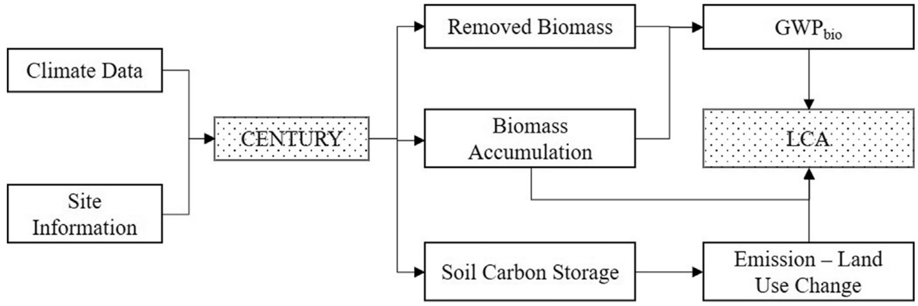

Fig. 1. The flowchart for the integration of the CENTURY model and LCA model in the GWP_{bio} accounting system.

also be included as climate change impact. Therefore, the CO_2 emission due to biomass harvest ($EMISSION_{T2}$) is calculated as follows:

$$EMISSION_{T2} = EMISSION_{luc} + EMISSION_{fossil} + EMISSION_{bio} + GROW_{com} \quad (2)$$

where $EMISSION_{bio}$ (i.e., $EMISSION_{tra} \cdot GWP_{bio}$) is climate change impact of biomass-derived CO_2 emission in the LCA model when treat biomass-derived CO_2 as non-neutral and $GROW_{com}$ is the biomass regrowth used to compensate biomass-derived CO_2 in the atmosphere. The climate change impact of biomass-derived CO_2 emission is defined as biogenic CO_2 emission. If biomass-derived CO_2 is non-neutral, a positive value of GWP_{bio} was multiplied to the biomass-derived CO_2 emission in the LCA model. The calculation of GWP_{bio} is determined by a metric method introduced by the IPCC with consideration of CO_2 decay in the atmosphere and biomass regrowth (Liu et al., 2017b). The detailed calculation of GWP_{bio} and $GROW_{com}$ can be found in the Supplemental information.

Therefore, the difference (D) between the two accounting systems is determined as follows:

$$D = EMISSION_{T1} - EMISSION_{T2} = EMISSION_{tra} - EMISSION_{bio} - GROW_{com} \quad (3)$$

2.2. Case study

2.2.1. Energy crop

The energy crop is *Caragana korshinskii* Kom. which is the main plantation in semi-arid and arid areas in the Loess Plateau for soil and water conservation in the "Grain-for-Green" Program in China. *C. korshinskii* is a rapid growing shrub with high tolerance to drought. Therefore, it is a primary choice for afforestation on the Loess Plateau to restore degraded land. The biomass yield of *C. korshinskii* plantation could be 1–2.5 Mg/ha/year. With high heating value (19 MJ/kg, Liu et al., 2015), low water content and high ability of regrowth, *C korshinskii* becomes an attractive energy crop in the Loess Plateau in China.

2.2.2. Study area

In this study, we assumed that the biomass harvest occurred in the Zhifanggou watershed in Ansai County, Shaanxi Province, China (36°46′28″–36°46′42″N, 109°13′03″–109°16′46″E; 1010–1431 m a.s.l.). This area has a semi-arid climate with typical hilly-gully loess landscape. The average annual temperature is 9.9 °C (1901–2012), and the annual precipitation is 499 mm (1901–2012). The precipitation is concentrated in July–September (about 70%). The soil texture is clay 65%, sand 24%, and silt 11% (Deng et al., 2017).

2.2.3. Climate input

The inputs of weather data in the CENTURY model were monthly precipitation, average daily maximum and minimum air temperature. The historical weather data from 1901 to 2012 was downloaded from the Climate Research Unit (CRU) of the University of East Anglia, UK (Mitchell and Jones, 2005). The means of the historical weather data were used in all simulations.

2.2.4. Model calibration

The CENTURY model is initially targeted to cropland/grassland simulation. The application of CENTURY to caragana plantation (shrubland/tree stand) requires calibration (Table S1). However, little information is known about *C. korshinskii* plantation on biomass accumulation and carbon storage, and exhaustive data are usually unavailable. Therefore, we only were able to complete a calibration at a regional-specific level (Loess Plateau). The optimal and maximum temperature for *C. korshinskii* was set to 20 and 40 °C (Wang et al., 1996). After a 2000-year spin-up, key parameters of the CENTURY model were calibrated by a biomass accumulation model (Fig. 2-a). The biomass accumulation model was a group of well-defined Logistic models to simulate the growth of *C. korshinskii* plantations in Guyuan, Ningxia Autonomous, China. The Logistic models had high coefficients of determination ($R^2 > 0.9$). The data points from age 1 to age 10 can be found in Fig. 2-a. The study area in Guyuan has a typical semi-arid climate and soil type in the Loess Plateau (Cheng et al., 2009). The sand, silt, and clay contents are 36%, 43%, and 21%.

2.2.5. Model validation

The CENTURY model was then validated for biomass yields from five different studies with a total of 18 observations (Table S2 in the Supplemental information). The model could explain 78% of the variation in the observed biomass yields on the Loess Plateau. There was a good relationship between observations (0.16–8.7 MgC/ha) and simulations (0.19–9.0 MgC/ha) across a range of stand age from 1 to 10 (Fig. 2-b). The unit of MgC is metric ton of carbon equivalent.

2.2.6. LCA model

The LCA model is a cradle-to-grave model. The system boundary includes site preparation, harvest, transportation, storage, preprocessing, pelletizing, distribution and final combustion in a boiler with waste disposal (Fig. 3). The functional unit (FU) was 1 ha of caragana plantation that was harvested.

The site preparation was a 1-year operation and included Disking, Plowing, and cultipacking. These processes were adjusted from Caputo et al. (2014)'s results. We assumed seeding was done by human power. The extraction of biomass had a 3-year rotation and required a harvester, a forage wagon and a wheel loader. The harvesting system was a 4GM-200 caragana stumping harvester with a baling function. The Wheel loader loaded up balers to the forage wagon, and forage wagon transported balers to a bigger truck. The balers were stored at plant site for further process. The average hauling distance of 60 km was assumed. The energy and material usage at plant site storage were adjusted from the published data (Emery and Mosier, 2012). The biomass loss at plant site storage was 5%. The pretreatment processes of caragana biomass were drying, grinding and hammer milling. The pretreatment processes and the pelletizing were based on the

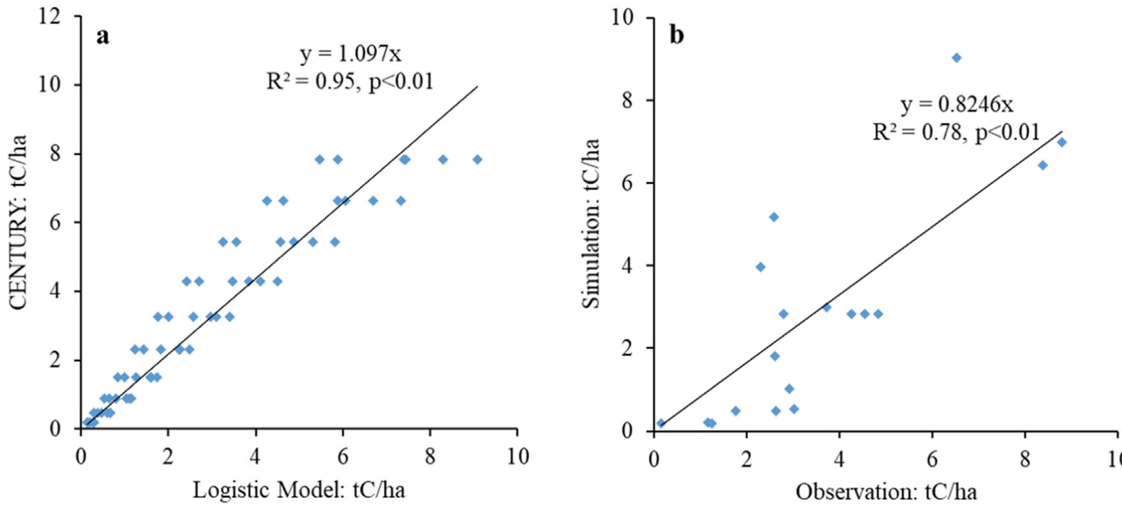

Fig. 2. Calibration (a) and validation (b) of the CENTURY model by published data.

measurements of the Idaho National Laboratory's (INL) Process Demonstration Unit (PDU) (Kenney et al., 2013). The water content of the feedstock at plant site was assumed 30% (w.b.). The feedstock requirement of pelletizing was <10% water content and less than 1/4″ in particle size. Therefore, 15% of the feedstock was needed to go through hammer mill (Kenney et al., 2013). We assumed no waste during pelletizing, and an average distribution distance of pellet fuel was 60 km. Pellet was combusted in an industrial boiler. The emissions were derived based on the properties of the feedstock (Brassard et al., 2014). All the other related background processes were from the ecoinvent 3.3 database (The EcoInvent Association, Switzerland).

The LCA model was developed by using the environmental modeling tool openLCA 1.6.3 (GreenDelta, Germany). The impact of GHG (greenhouse gas) emissions was calculated using 100-year global warming potentials (Myhre et al., 2013). All emissions were converted to kg CO_2 equivalent (kg CO_2 eq).

2.2.7. Sensitivity analyses

We conducted a series of sensitivity analyses on the effects of climate change (temperature and precipitation) and biomass yield on carbon emissions (Table 1). All the factors were set to have 10% and 20% increase, and 10% and 20% decrease to the base case. The effects of temperature and precipitation were analyzed as major climate change parameters. The climate condition could significantly affect the biomass yield of caragana plantation. However, the biomass yield of caragana plantation could also be influenced by other factors, such as management practice and degradation of soil fertility. Therefore, the sensitivity of biomass yield was also studied. The change of biomass yield was obtained by proportionally changing every biomass component.

3. Results

3.1. Decay of biomass-derived CO_2 emission

If no biomass regrowth is used to compensate biomass-derived CO_2 emission in the atmosphere, the decay of biomass-derived CO_2 will follow the trajectory of fossil fuel-derived CO_2. However, with the compensation of biomass regrowth, the biomass-derived CO_2 can decay much faster than fossil fuel-derived CO_2. Fig. 4-a shows the simulation of biomass regrowth by month after stumping harvest. The accumulation of total biomass within the 3-year rotation (1.699 MgC/ha) is higher than the biomass removal (0.618 MgC/ha). Therefore, the

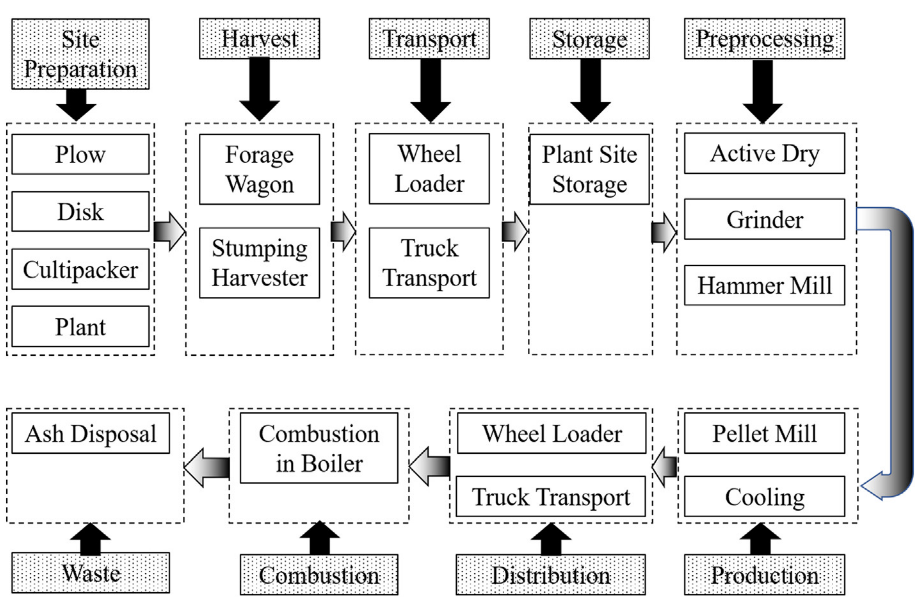

Fig. 3. The LCA system boundary of the caragana-to-pellet system.

Table 1
Parameter configurations of sensitivity analysis.

Parameter	Base case	Sensitivity setting	Note
Temperature (°C)	9.9	7.92, 8.91, 10.89, 11.88	The sensitivity settings are +20%, +10%, and −20%, −10% from the base case.
Precipitation (mm)	499	399.2, 449.1, 548.9, 598.8	
Biomass yield (MgC/ha)	0.618	−20%, −10%, 10%, 20%	

remaining biomass-derived CO_2 in the atmosphere is fully compensated at the end of the second year after harvest (Fig. 4-b). Based on the decay trajectory of biomass-derived CO_2 emission from the caragana-to-pellet system, the GWP_{bio} value is 0.044.

3.2. Difference between the accounting systems

In the conventional accounting system, the harvested biomass is 0.618 MgC/ha which is accounted as the emission ($EMISSION_{tra}$) of 2.237 $MgCO_2$/ha ($MgCO_2$ is the metric ton of CO_2 equivalent emission). In the conventional LCA model (presuming carbon neutrality), the CO_2 equivalent GHG emissions are 0.651 $MgCO_2$/ha ($EMISSION_{fossil}$). When the global warming potential of biomass-derived CO_2 is included ($GWP_{bio} = 0.044$), the fossil fuel-derived and biogenic GHG emissions of the caragana-to-pellet system is 0.718 $MgCO_2$/ha ($EMISSION_{fossil} + EMISSION_{bio}$). This is a 10% increase in comparison to the conversional LCA. The biomass accounted for compensation in the base case is 1.91 $MgCO_2$/ha ($GROW_{com}$). Therefore, the difference between the two accounting systems is 0.261 $MgCO_2$/ha.

3.3. Sensitivity analyses

By changing the annual precipitation and the annual average temperature, the GWP_{bio} values are changed accordingly. The annual average temperature has a more significant effect on GWP_{bio} than the annual precipitation (Table 2). A 20% increase in annual temperature can cause a decrease of GWP_{bio} up to 3.2%, whereas a 20% increase in the annual average precipitation can increase GWP_{bio} by 0.7%. The highest GWP_{bio} (0.0453) is found when reducing the annual average temperature by 20%, and the lowest (0.0429) is obtained by increasing the annual average temperature by 20%. No significant effect of biomass yield is found on GWP_{bio}.

As Fig. 5 shows, the decrease of the annual average temperature can enlarge the difference of CO_2 emission between the two accounting systems. The increase of annual precipitation and biomass yield can increase the difference. However, the effect of temperature is more significant. A 20% decrease of the annual average temperature can induce a 28.2% increase in the difference between the two accounting systems. This is the highest increase among the three parameters (temperature, precipitation and biomass yield). The smallest effect is found by changing the annual precipitation. A 20% increase in annual precipitation can increase the difference of CO_2 emission between the two accounting systems by 8.5%.

4. Discussion

4.1. Biomass regrowth and GWP_{bio}

The CENTURY model was calibrated and validated by regional data of caragana field inventory on the Loess Plateau. Although the study of carbon dynamics of caragana plantation is rare, the published data collected in this study were representative of the typical climate and soil conditions on the Loess Plateau (see the Supplemental information). The simulations could explain most of the variation of the observations. However, the simulation by adjusted CENTURY model would be too conservative in comparison to empirical data of short rotation willow coppice (Caputo et al., 2014). One possible reason is that the density of the caragana plantation was improperly managed. The density of the observations ranges from 500/ha to 3500/ha. An increase of plantation density within a reasonable range (about 5000 plants/ha) could effectively increase the yield of biomass (Yang et al., 2010). Another reason could be that only growth of caragana plantation without stumping harvest was calibrated. However, the growth of coppice would be much faster after the first rotation because of the establishment of the root system (Sun et al., 2005; Caputo et al., 2014).

For calculation convenience, the pellet production was assumed to be combusted and emit CO_2 as a one-time pulse right after harvest. However, in the real world, a one-time pulse is rare to occur. The delay of pellet combustion could reduce the GWP_{bio} value and increase the amount of biomass regrowth to compensate for the emission. In our simulation, the sum of aboveground and belowground biomass accumulation was accounted as compensation of the biomass-derived CO_2 emission, while only a portion of aboveground biomass was removed for bioenergy. Therefore, the biomass-derived CO_2 was usually fully compensated within two years. Therefore, zero GWP_{bio} will be obtained if the pellet is retained in the bags for more than two years. In some published studies, the GWP_{bio} even could be negative when the CO_2 emission from the biomass materials was delayed (Breton et al., 2018).

In our simulation of the caragana plantation, the GWP_{bio} value (0.044) was slightly higher than 0. The value was close to the published value (Cherubini et al., 2011). The positive value indicates a positive climate change impact of biomass-derived CO_2 emission. If the length of

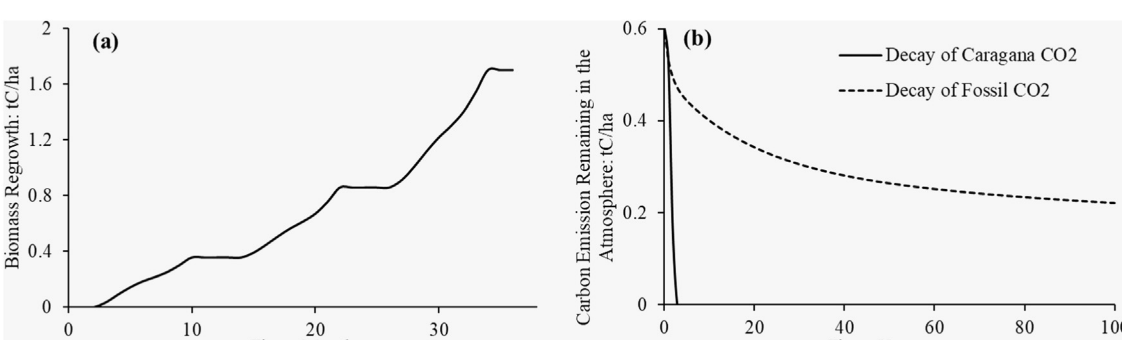

Fig. 4. Caragana biomass accumulation after harvest (a) and decay of caragana biomass-derived CO_2 emission in the atmosphere.

Table 2
The variation of GWP_{bio} in sensitivity analysis.

Parameter	−20%	−10%	0%	+10%	+20%
Precipitation	0.0441	0.0442	0.0443	0.0445	0.0446
Temperature	0.0453	0.0450	0.0443	0.0437	0.0429
Yield	0.0443	0.0443	0.0443	0.0443	0.0443

rotation was elongated, the GWP_{bio} value would increase significantly. For forest stand with a 100-year rotation, the GWP_{bio} value was high to 0.2–0.6 (Cherubini et al., 2011; Liu et al., 2017b).

4.2. Difference between the two accounting systems

When accounting the biogenic CO_2 emission in the atmosphere, carbon equivalent mass was converted to CO_2 equivalent by multiplying 3.667. The multiplier 3.667 is the inverse of the mass fraction of carbon in CO_2. In the LCA model, only a 10% increase in global warming impact in carbon non-neutral scenario was obtained in comparison to carbon neutral scenario. This is because of the high conversion rate (100%) of pellet production and a low proportion of biogenic CO_2 in the life cycle CO_2 emission of pellet production. If the caragana biomass is converted to ethanol or electricity, the weight of biogenic CO_2 will increase due to the low energy efficiencies of ethanol and electricity production (Liu et al., 2017a). For those pathways of biomass utilization (e.g., biomass-to-ethanol, biomass-to-electricity), the fossil fuel-derived and biogenic GHG emissions could be higher than fossil fuel if the GWP_{bio} method is applied (Liu et al., 2017b). However, in the global warming impact assessment of biomass utilization, the GWP_{bio} method is more realistic and allows a much fair comparison with fossil fuels.

Although the including of a non-zero GWP_{bio} could increase the fossil fuel-derived and biogenic GHG emissions, the total impact ($EMISSION_{T2}$) was still lower than the impact by the conventional method ($EMISSION_{T1}$). In this study, we considered the global warming potential of biomass-derived CO_2 emission during its stay in the atmosphere and the accelerated decay of biomass-derived CO_2 by the compensation of biomass regrowth. Therefore, the GWP_{bio} accounting method obtained less CO_2 emission than the traditional method for biomass utilization. If the biomass requires long period to be fully compensated (i.e., woody biomass), the difference will be much broader because the decay of biomass-derived CO_2. The GWP_{bio} accounting system, thus, would encourage more utilization of biomass. However, the GWP_{bio} accounting system should not be used in a carbon inventory at a national scale, because the concept of GWP_{bio} is only developed to estimate climate change impact of biomass-derived CO_2 emission.

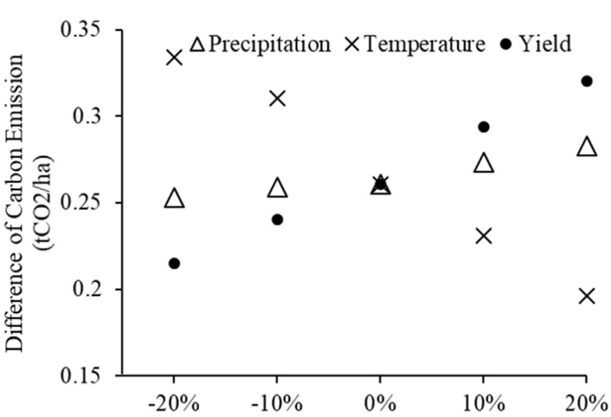

Fig. 5. Sensitivities of CO_2 emission difference to precipitation, temperature, and biomass yield.

Moreover, in both accounting systems, emission due to land use change was also alleged to include. Although this emission is not actually calculated in this study, the emission in the field due to biomass harvesting is a noticeable portion (Searchinger et al., 2009; McKechnie et al., 2010), and should not be excluded.

4.3. Model performances

In the GWP_{bio} accounting system, the variations of GWP_{bio} values were determined by the rate of biomass accumulation. A decrease of biomass accumulation rate rises the GWP_{bio} value, and a high GWP_{bio} value indicates a high difference between the two accounting systems. In the CENTURY model, air temperature and precipitation are important parameters in affecting biomass accumulation. Therefore, the change in air temperature and precipitation could significantly change the GWP_{bio} values. The increase in air temperature will increase surface evaporation and caragana leaf transpiration. Therefore, the biomass growth will be inhibited by high air temperature (i.e., drought). However, the decrease in air temperature only has a positive effect on biomass within an optimal temperature range (Hatfield and Prueger, 2015). The increase of biomass yield could also increase the biomass accumulation rate. However, no effect on GWP_{bio} can be found due to the proportional increase of every biomass components. Although there is no effect on GWP_{bio}, the increase of biomass yield can broaden the difference of the two accounting systems because of increased availability of biomass per hectare. The sensitivity of the hauling distance on the difference between the two accounting systems was not analyzed. This is attributed to the low global warming impact percentage of biomass hauling process (<1%) in the cradle-to-grave LCA (Saud et al., 2013).

5. Conclusion

Many researchers have been aware that the biomass-derived CO_2 emission may not be neutral to climate change. A metric method to account for the global warming potential of biomass-derived CO_2 (GWP_{bio}) was proposed. In this study, we integrated the carbon dynamic model (CENTURY model) with LCA model (considering GWP_{bio}) to assess the climate change impact of biomass utilization. Due to the short rotation of caragana plantation and fast biomass accumulation after harvest, GWP_{bio} values were around 0.044. In the LCA model of the caragana-to-pellet system, the climate change impact of biomass-derived CO_2 emission was a small portion of the total life cycle emissions. By the comparison of the GWP_{bio} accounting system and the conventional accounting system, a lower total impact by the GWP_{bio} accounting system was found. This indicated the application of GWP_{bio} accounting system would encourage the utilization of biomass and allow a fair comparison to fossil fuels. This accounting system is a realistic method to assess the climate change impact of biomass utilization. In the sensitivity analysis, we found that the GWP_{bio} was sensitive to the air temperature and precipitation that could significantly affect biomass accumulation. With fast biomass accumulation, a low GWP_{bio} was found and a large difference between the two accounting systems should be expected. However, simply linear change of biomass yield could broaden the difference without any effect on GWP_{bio},

Authors' contribution

In this study, Weiguo Liu is responsible for the scientific work and finished the writing of the manuscript. Qiuan Zhu accompanied the data collection and analysis. Xiaolu Zhou and Changhui Peng provided critical comments and improved the manuscript.

Competing interest

The authors declare that they have no competing interests.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2018.11.039.

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